The Advanced High-Temperature Reactor (AHTR)

Dr. Charles Forsberg

Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831-6179
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

Briefing for Commissariat a l Energie Atomique (CEA)
(French Atomic Energy Commission)
High Temperature Materials Laboratory (Bld. 4515); Conference Room 114
Oak Ridge National Laboratory
Oak Ridge, Tennessee
July 17, 2003

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The AHTR History

- The AHTR is a joint effort
  - Oak Ridge National Laboratory (Charles Forsberg (ORNL)
  - University of California-Berkeley (Per Peterson)
  - Sandia National Laboratories (Paul Pickard)
- AHTR incorporates 5 older technologies
  - Molten salt coolant (1960s)
  - Gas-cooled reactor coated-particle fuel (1970s)
  - S-PRISM/MHTGR passive safety (1980s)
  - Helium Brayton power cycle (1990s)
  - Corrosion control in clean salts (1960s forward)

AHTR Overview

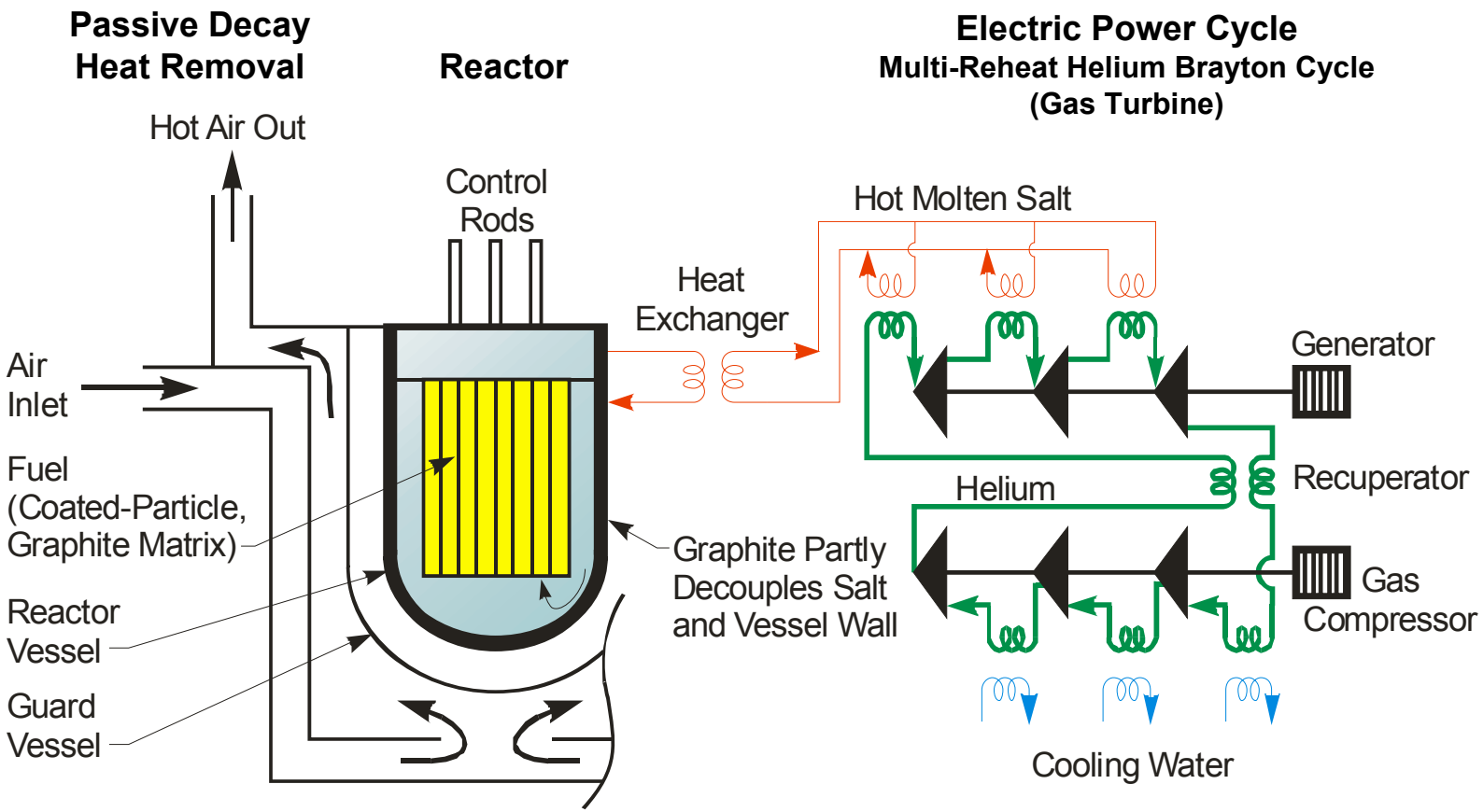
Large, Passively Safe, High-Temperature Reactor for Electricity and Hydrogen Production

Large Reactor (>2000 MW(t)) to Improve Economics
Safety Basis of a Modular High-Temperature Reactor
High-Temperature Reactor (80% Commonality with Helium Gas-Cooled Reactors)

Comparison of Different High-Temperature Reactors

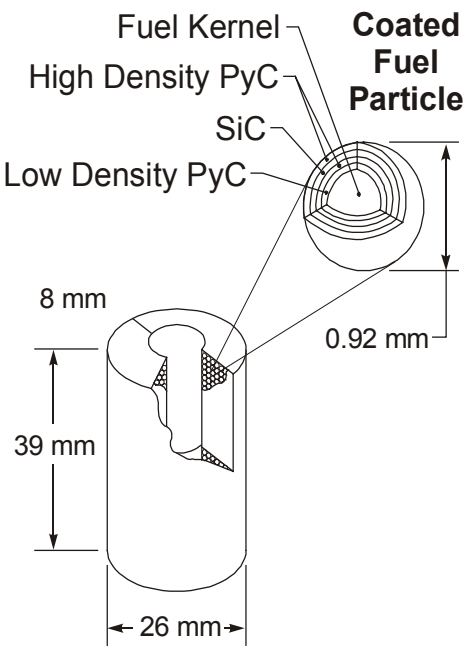
Property	*AHTR*	*VHTR*
Fuel	Coated Particle	Coated Particle
Neutronics	Epithermal	Epithermal
Power Cycle	Helium Brayton	Helium Brayton
Safety System	Passive	Passive
Coolant	*Molten Salt*	*Helium*
Pressure	Atmospheric	High Pressure
Power Level	2400 MW(t)	600 MW(t)

The Advanced High Temperature Reactor

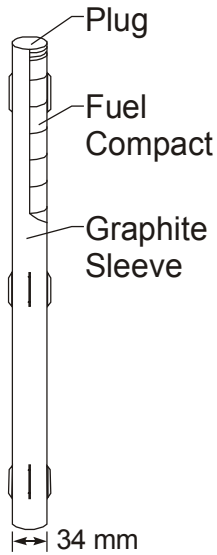


The AHTR Uses Coated-Particle Graphite Fuels

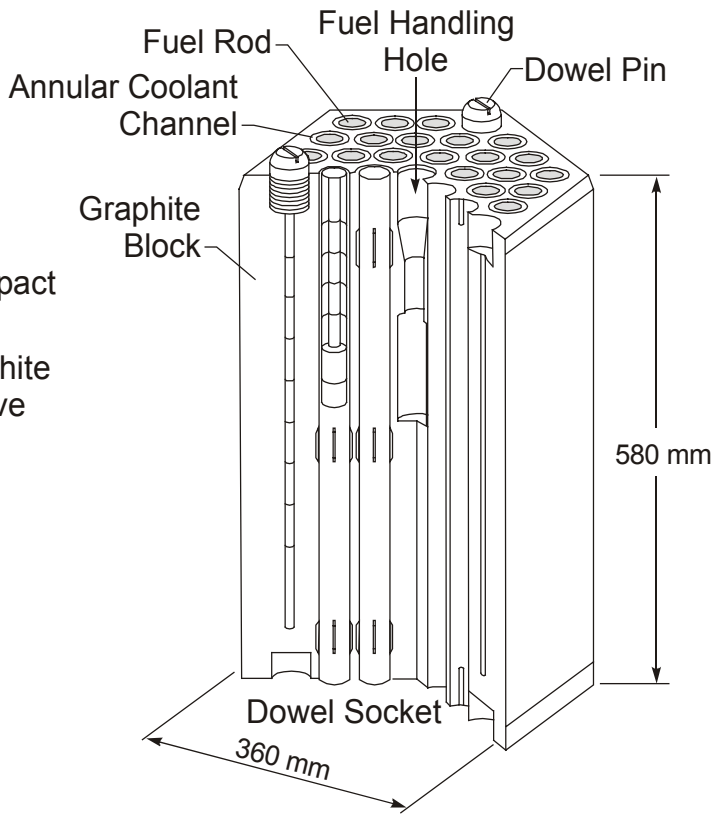
(Similar to Helium-Cooled Reactors; Prismatic or Pebble-Bed Fuel)



Fuel Compact



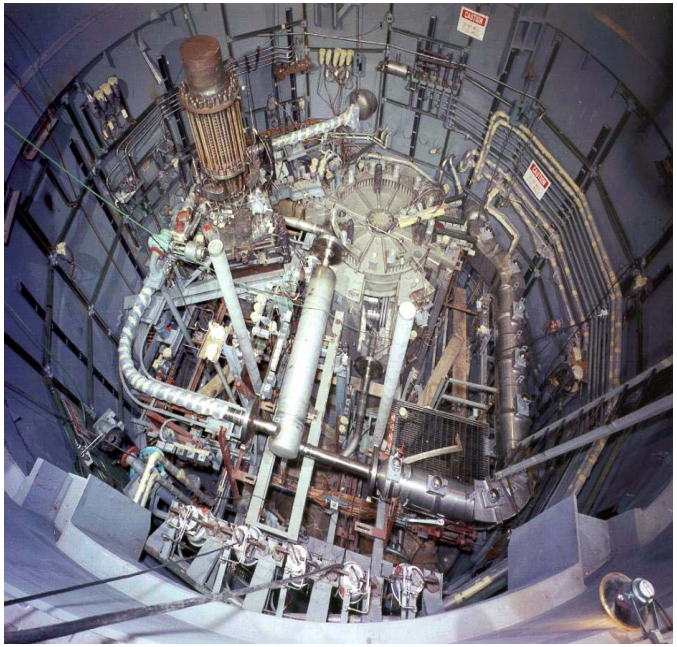
Fuel Rod

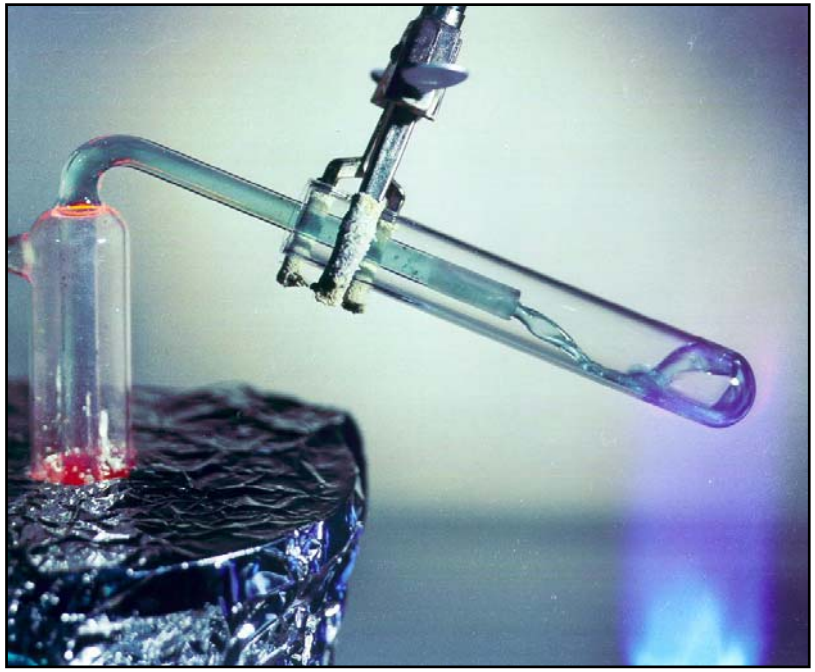


Fuel Block

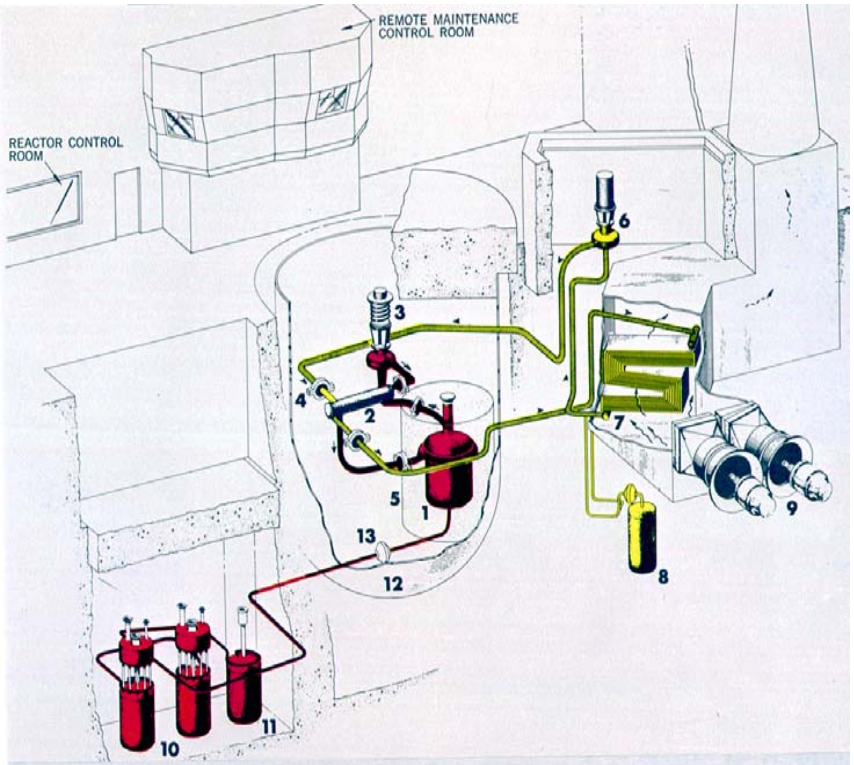
AHTR Molten Salt Coolants Have Several Advantages: Good Heat Transfer, Low Pressure, and Transparent

Technology originally developed for Aircraft Nuclear Propulsion Program and Molten Salt Reactor Program (left): Potential Uses Include AHTR, Heat Transfer Loop Between Reactor and Hydrogen Production Plant, and Fusion Energy Plants)





The AHTR Is NOT a Molten Salt Reactor (MSR)

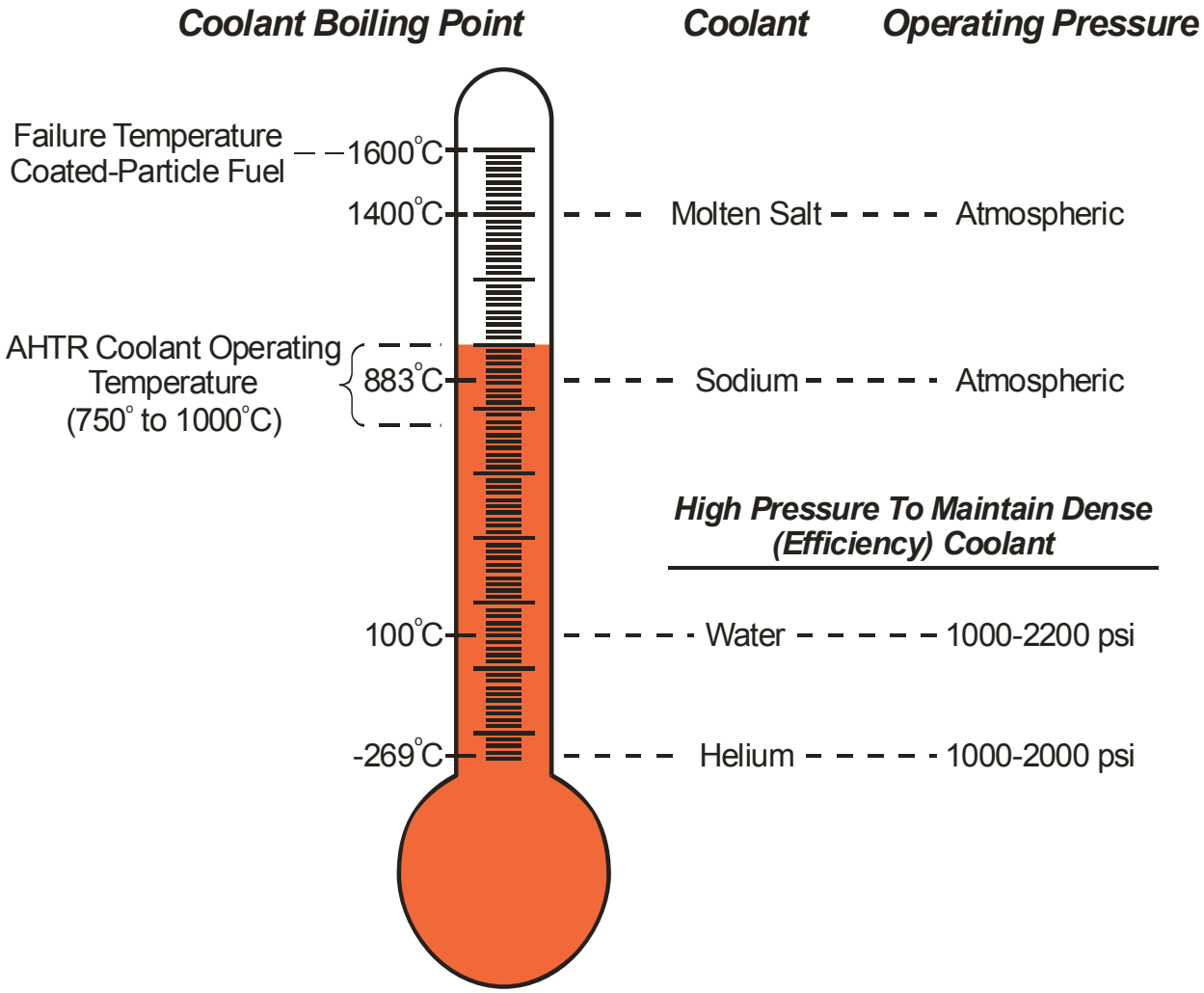


1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

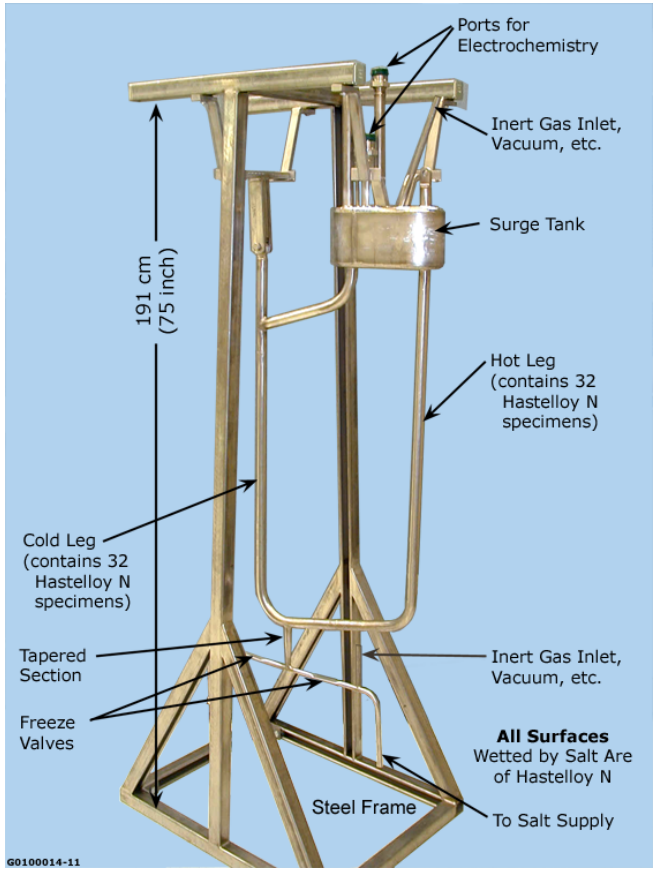
- MSR (Left)
  - Fuel dissolved in the molten salt
  - Molten-salt reactor experiment (1965-1969)
- AHTR
  - Solid fuel
  - Clean molten-salt coolant
  - Uses MSR experience
    - Secondary MSR heat-transfer system used clean molten salts
    - MSR secondary system: green piping (left)

AHTR Operates at Atmospheric Pressure

(Large Margins to the Boiling Point and Boil-Off Before Fuel Failure)

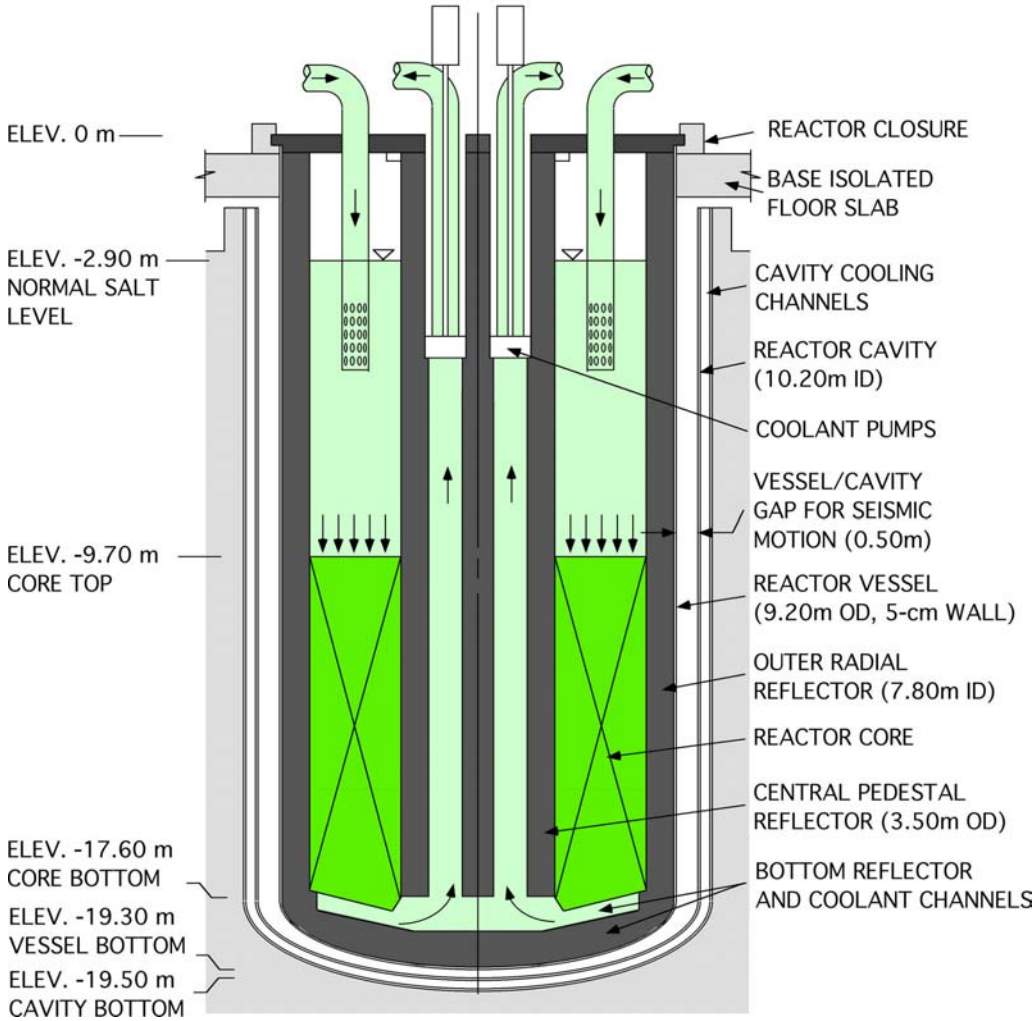


Metal Alloys In the 1970s Were Developed For Molten-Salt Industrial Service To 750ºC



- AHTR uses clean salts (Simpler chemistry)
- Metals are non-reactive (noble) in contact with clean salts
- ORNL LDRD test loop evaluating corrosion resistance at higher temperatures (Left)

Conceptual 2400 MW(t) AHTR Vessel



- **Transportable vessel**
  - **Same size as S-PRISM 1000 MW(t) vessel**
  - **Similar size to 600 MW(t) GT-MHR reactor vessel**
- **Down-flow molten salt**
- **MHTGR annular core**

Decay-Heat Safety Strategy: Decay Heat to the Reactor Vessel Wall With Silo Cooling

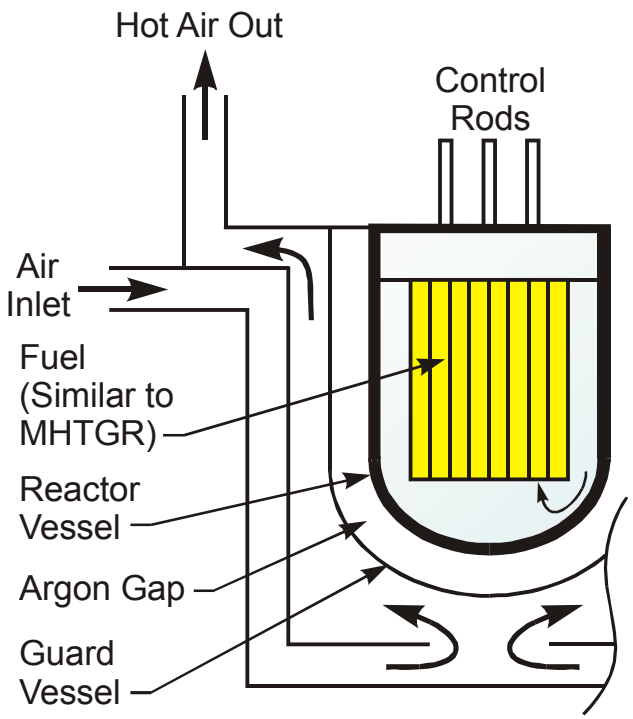
Same approach as Modular High-Temperature Gas-Cooled Reactors and General Electric Sodium-Cooled Modular S-PRISM

Molten Salt Allows Larger Reactor Sizes

In an Emergency, Decay Heat is Transferred to the Reactor Vessel and Then to the Environment

(Example: GE-PRISM approach; Other options: GT-MHR and Pebble Bed)

Passive Decay Heat Removal **Reactor**

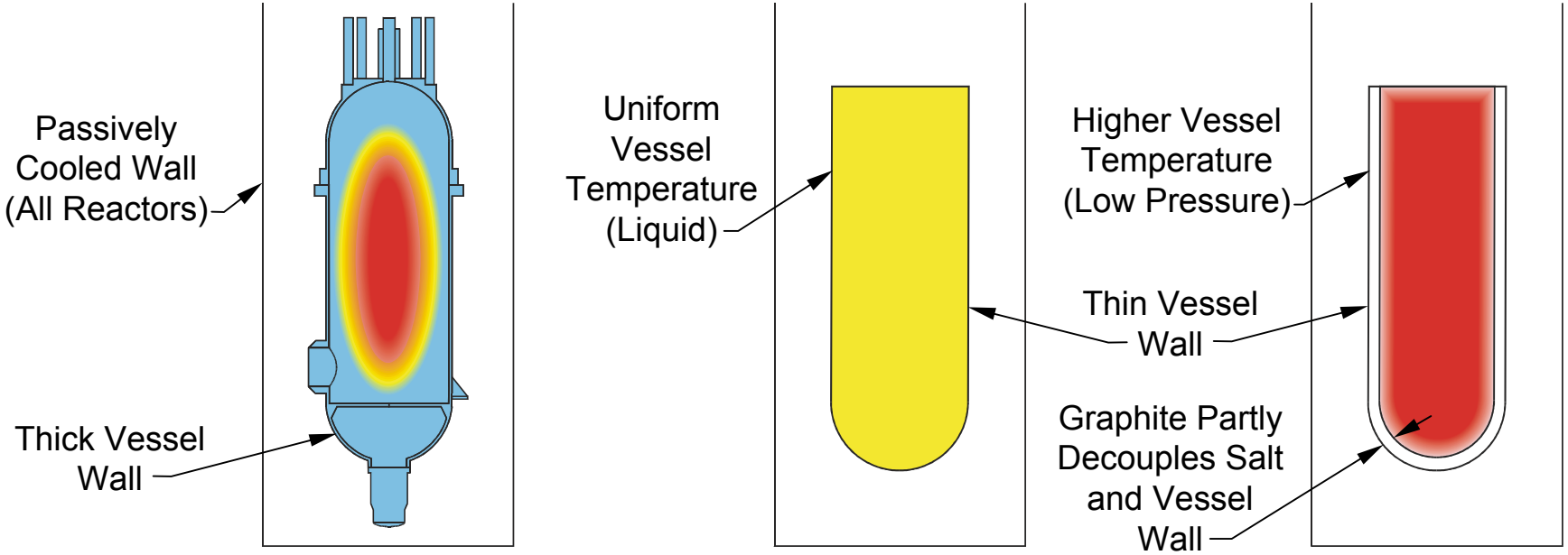


Decay-Heat Cooling System Characteristics

- Similar to GE S-PRISM (LMR)
- Argon Gap
  - Heat Transfer ~T^4
  - Thermal Switch Mechanism
- Heat Rejection: Temperature Dependent
  - LMR: 500-550°C [~1000 Mw(t)]
  - AHTR: 750-1000°C [>2000 Mw(t)]
- High Heat Capacity
  - Molten Salt and Graphite
  - High Temperature (Limited-Insulation of Vessel from Hot Salt)

Evolution of Passive Decay Heat Removal Systems Enables Design of Larger Reactors

Reactor	MHTGR	S-Prism	AHTR
Coolant	Helium	Sodium	Molten Salt
Power	600 MW(t)	1000 MW(t)	>2000 MW(t)
Limitation	Conduction	Sodium Boiling Point	Vessel

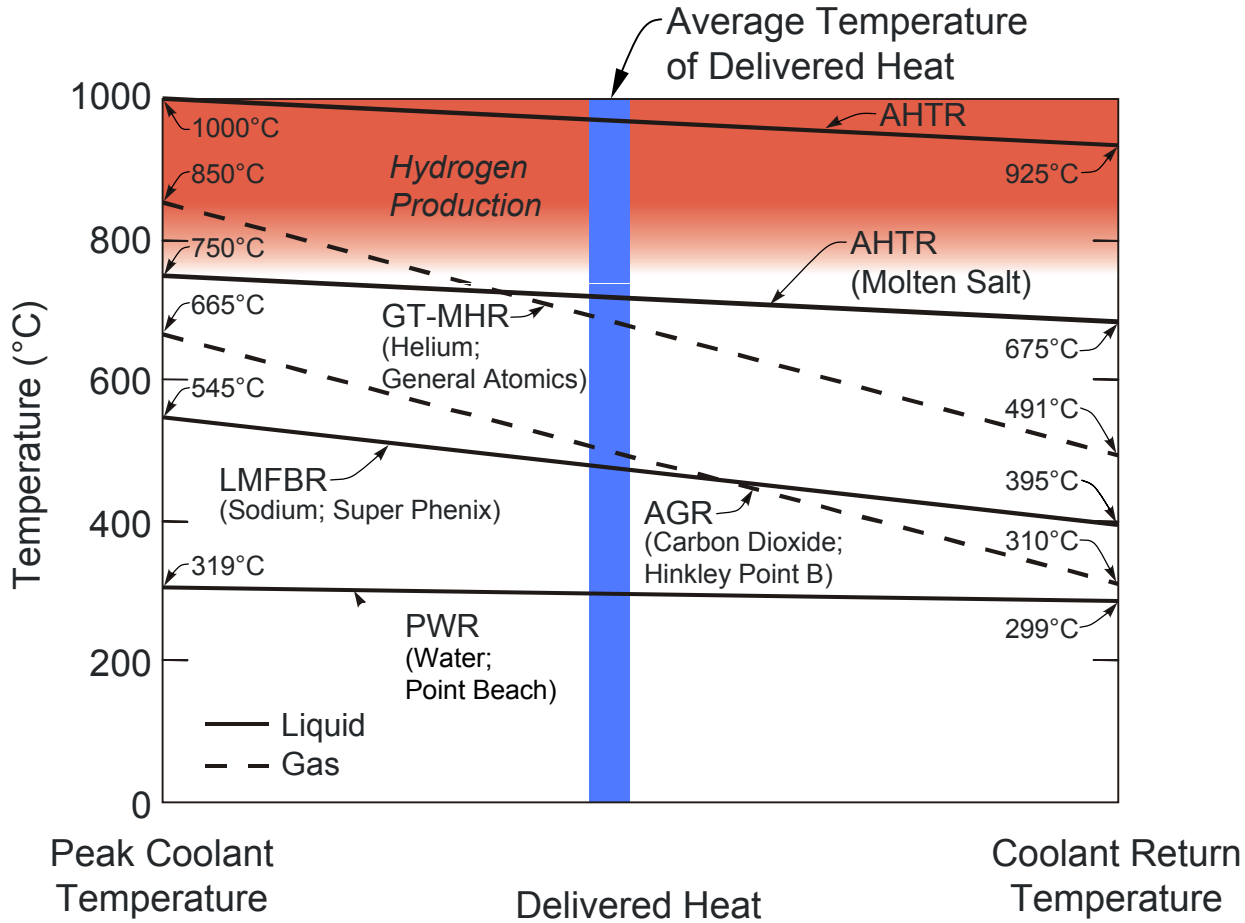


AHTR Delivers High-Temperature Heat With Lower Reactor Peak Temperatures

Peak Reactor Temperatures Are Lower In Liquid-Cooled Reactors Than Gas-Cooled Reactors

Liquid-Coolants Minimize Peak Coolant Temperatures for a Given Temperature of Delivered Heat

AHTR Lowers Peak Coolant Temperatures

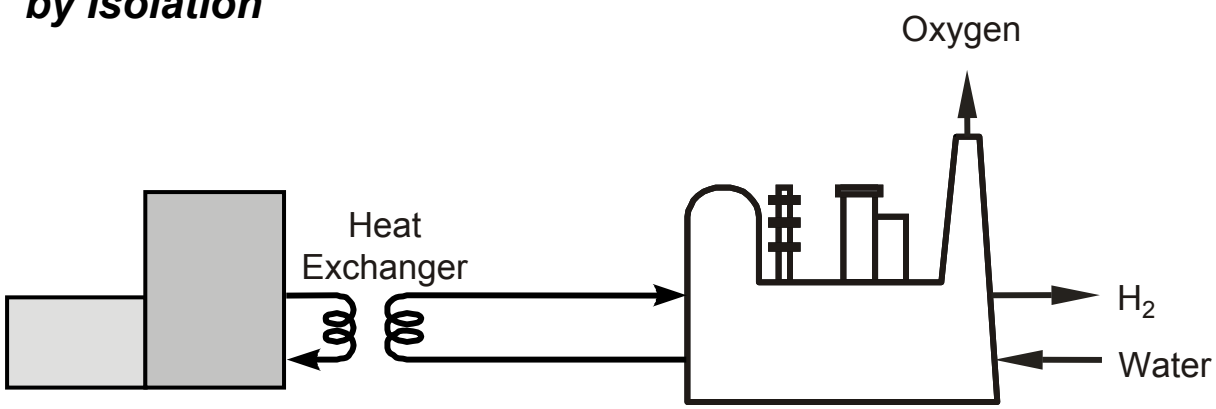


Molten Salts Preferred For Transfer of Heat From Reactor to Physically-Separated Hydrogen Production Facility

(1970s German Studies)

Nuclear Safety by Isolation

Hydrogen Safety by Dilution



Loop Heat Transfer Comparison
[50 MW(t)]

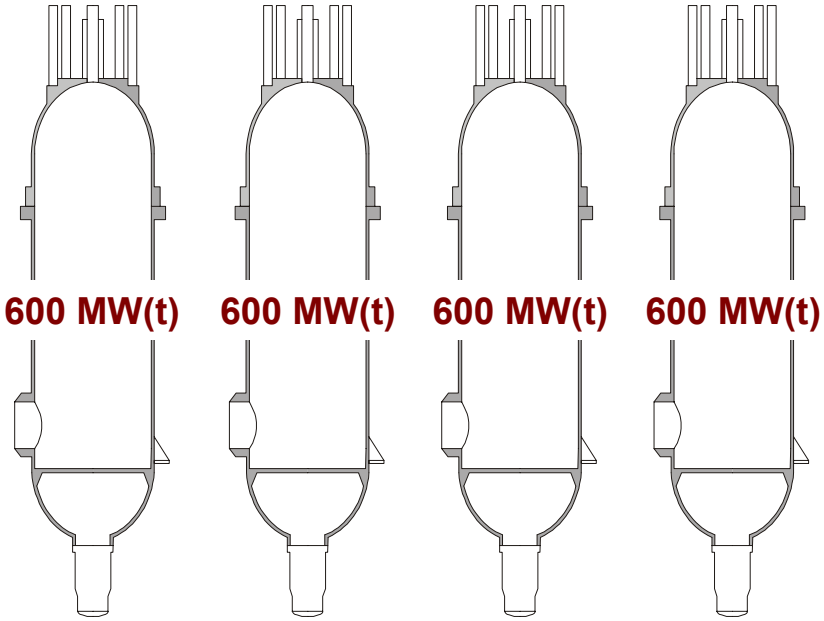
Characteristic	Salt	Helium
Pressure (bar)	1	70
Velocity (m/s)	4	40
Temperature Drop (°C)	200	200
Pipe Diameter (m)	0.25	1.2
Relative Pumping Power	1	45

Economics

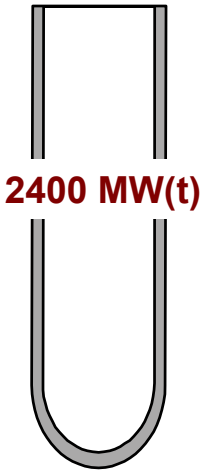
Larger Reactors Have the Potential for Lower Capital and Operating Costs

Equipment Comparisons Suggest AHTR Capital Cost Per MW(t) Is Less Than a Modular Reactors

Pressure Vessels For 2400 MW(t) of HTGRs



Low-Pressure Vessel For 2400 MW(t) of AHTR



Simple Scaling Laws Estimate AHTR Per Kilowatt Capital Cost at 60% of Modular High-Temperature Reactor

Potential for Better Economics Than Light-Water Reactors *But No Definitive Economic Comparison*

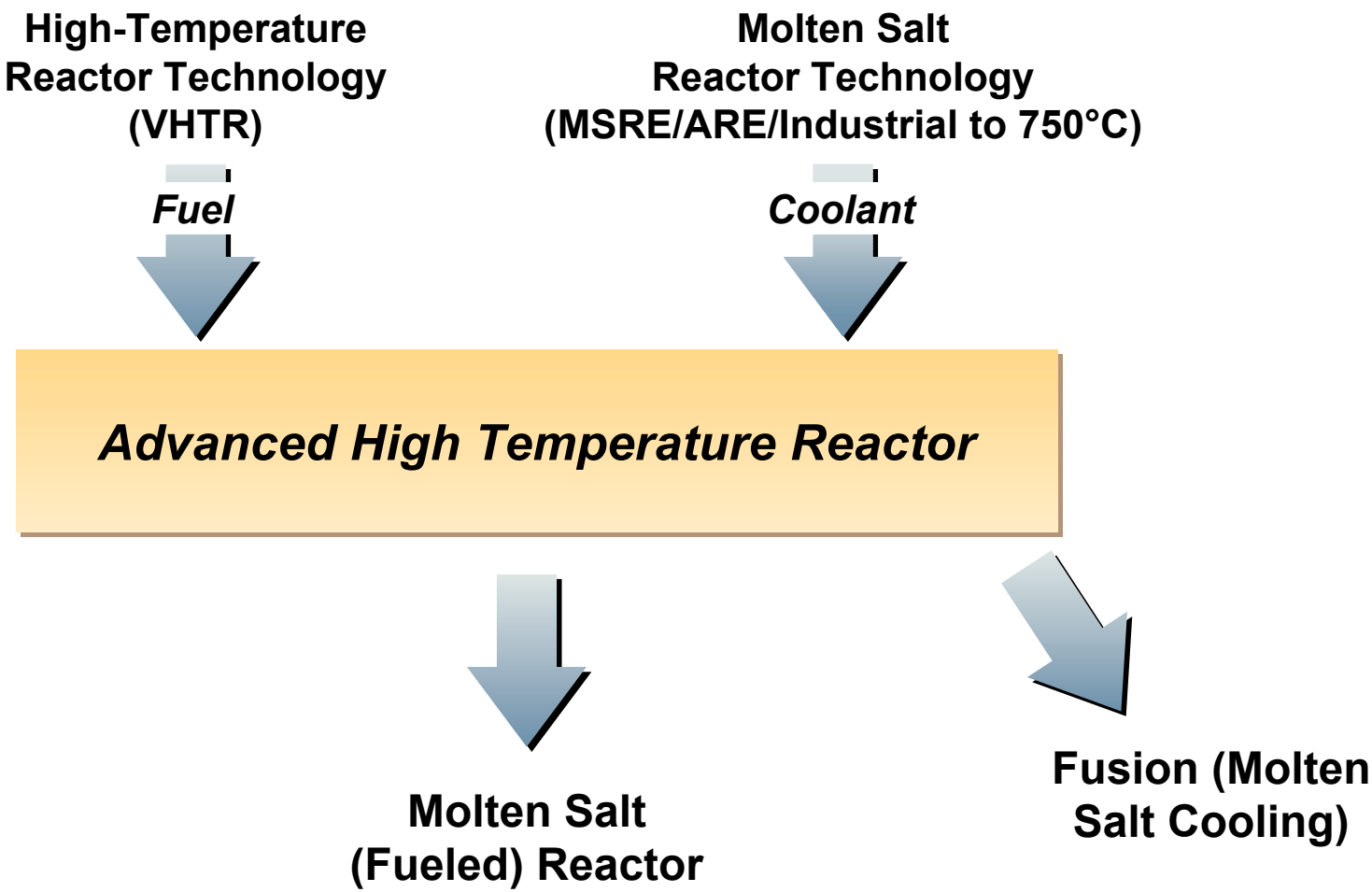
- LWR technology is significantly different; thus, simple scaling comparisons can not be made
- Potential economic advantages of AHTR
  - Higher thermal-electric efficiency (50% versus 33%)
    - Fuel savings
    - Smaller secondary systems
  - Brayton helium cycle (Smaller than steam turbine)
  - Low pressure containment

Technical Status

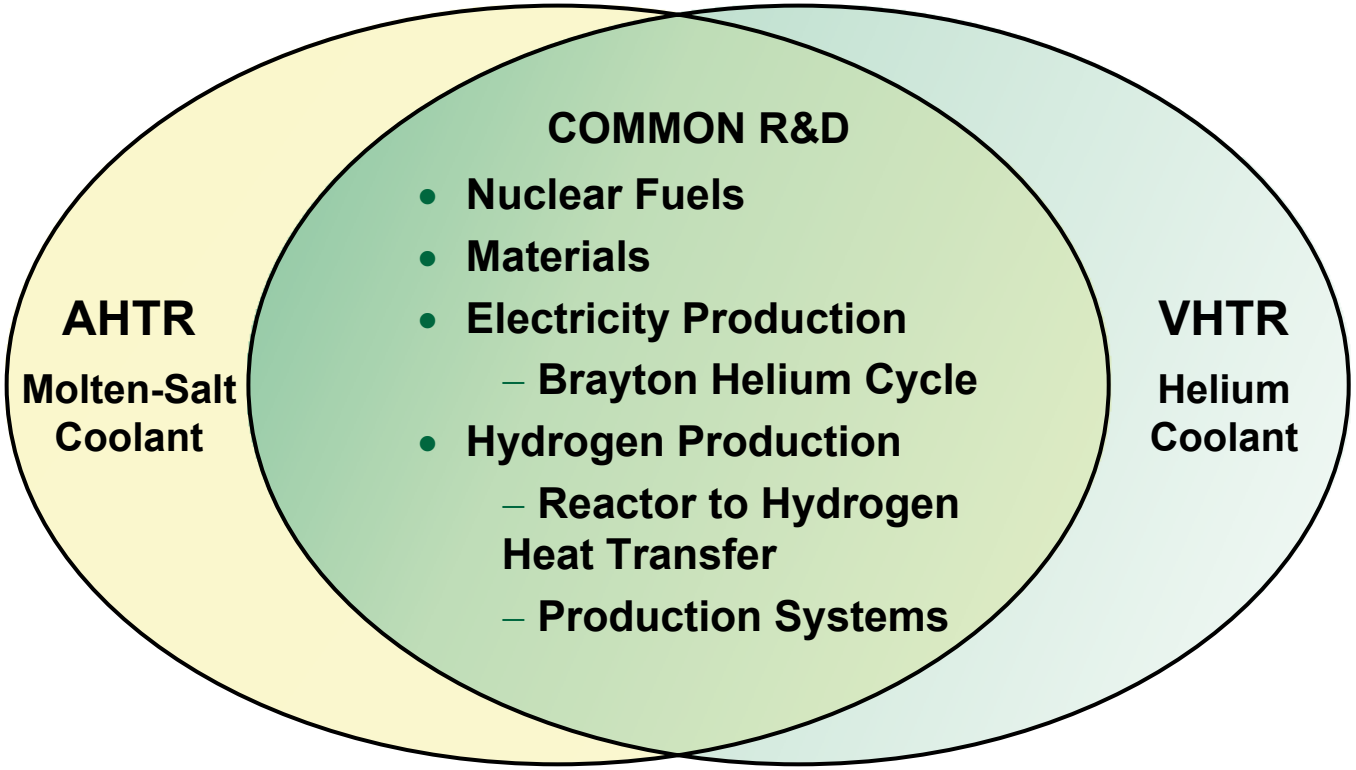
Shares Many R&D Issues with VHTR

Some Unique Issues

Evolution of AHTR and Other Technologies



The R&D Requirements for the Molten-Salt-Cooled AHTR and Helium-Cooled VHTR Have Much In Common



Unique AHTR R&D Issues

(Excluding Those In Common with MHTGR)

- Reactor
  - Materials
    - Most issues identical to molten-salt heat-transfer loop between reactor and hydrogen plant
    - Some unique issues
  - Core design
  - Choice of salt (Neutronics, melting point, etc)
- Systems
  - Decay Heat Cooling System
    - Defines maximum plant size
  - System Tradeoffs

Conclusions

- AHTR goals
  - Improve economics with larger high-temperature reactor
  - Same passive safety basis as modular reactors
  - Commonality with helium-cooled reactors
- Technology foundation based on
  - Modular high-temperature gas-cooled reactors
  - Molten salt reactors
- New reactor concept
  - Shares many R&D issues with VHTR
  - Several AHTR specific issues
- Strengthens basis for high-temperature reactors

BACKUP SLIDES

Molten Salt Options

- Choice of molten fluoride salt is dependent upon multiple factors
  - Neutronics
  - Economics
  - Properties (melting point, heat transfer, corrosion potential, solubility, volatility)
- Leading candidates were investigated during the Aircraft Nuclear Propulsion Program
  - Simple alkali halides: FLiNaK (FLiNaRb)
  - Zr-containing salts: ARE salt $NaF\text{-}ZrF_4$ (and ternary systems)
  - Be-containing salts: MSRE coolant salt-$^7Li_2BeF_4$

Molten Fluoride Salts Are Compatible With Graphite-Based Fuels

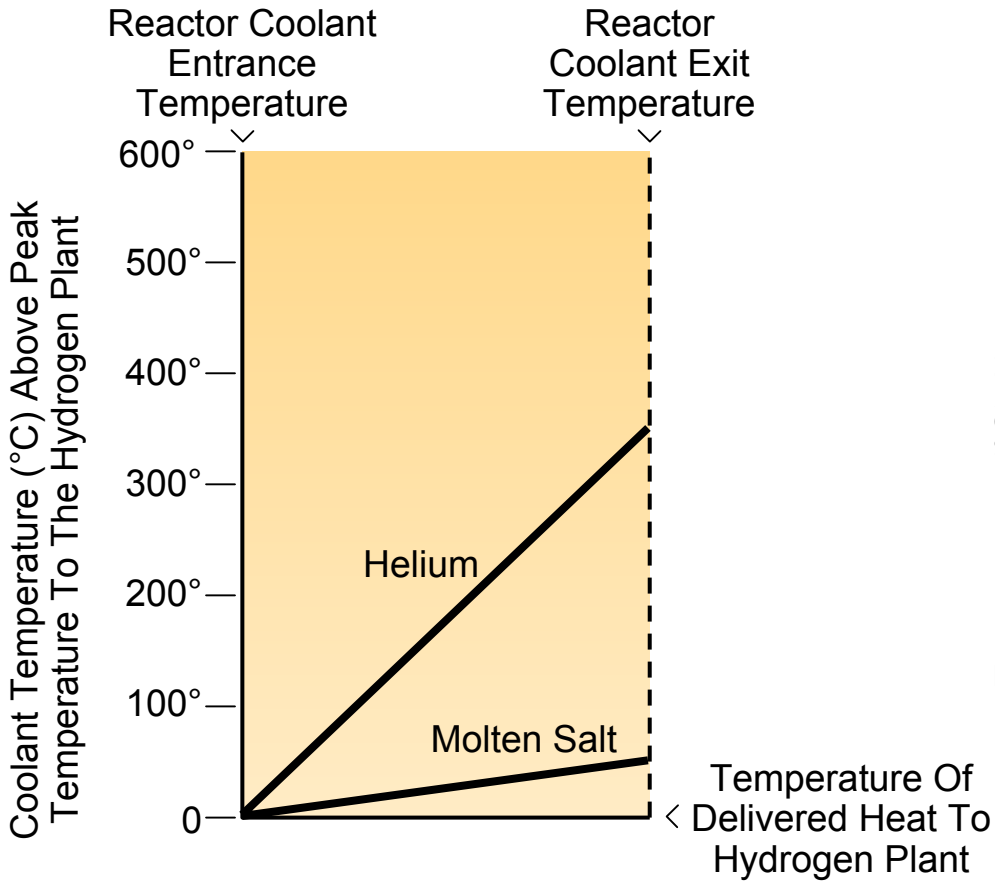
- Molten Salt Reactor Experiment showed that salt and graphite are compatible
- Industrial experience
  - Hall aluminum production since 1890s
  - Graphite baths
  - AlF_3/NaF_3 salt
  - 1000°C

Metals Are Noble (Stable) When In Contact With *Clean* Molten Salts

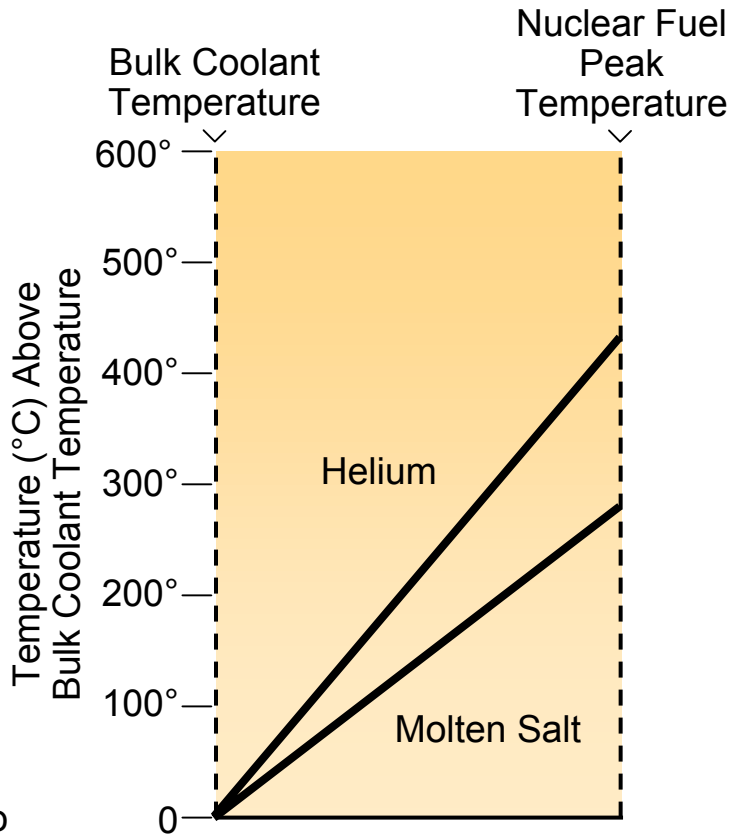
Element	Free Energy of Formation (1000°K; kcal/mole)
NaF	-112.
RbF	-112.
ZrF_4	-97.0
CrF_2	-75.2
FeF_2	-66.5
NiF_2	-55.3

The Liquid-Cooled AHTR Reduces Reactor & Fuel Temperatures Compared to Gas-Cooled Reactors

Bulk Coolant Temperature Rise Across Reactor

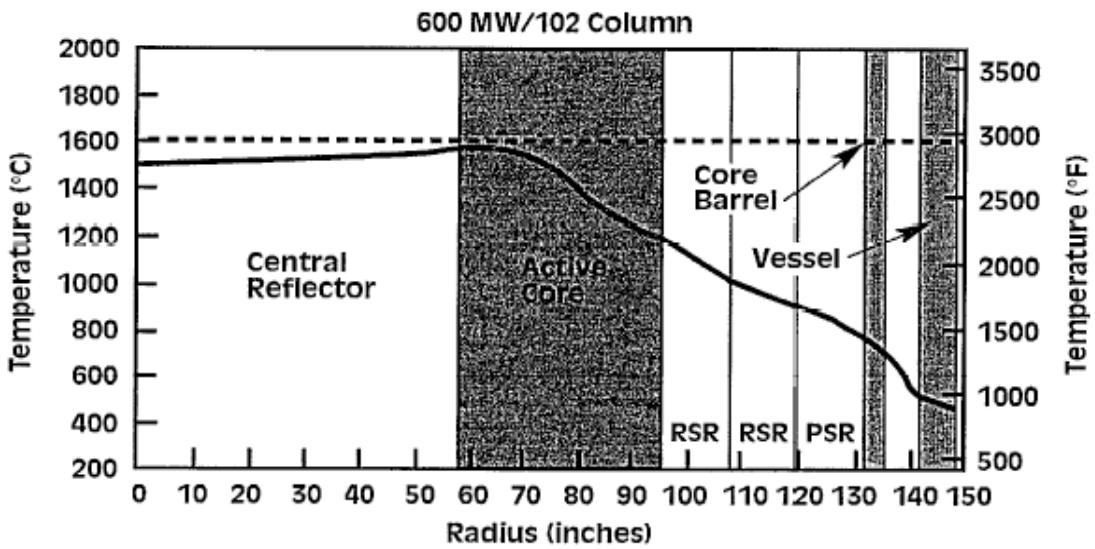


Temperature Rise From Coolant To Fuel Centerline



Helium-Cooled Reactors Require Large Temperature Drops To Remove Decay Heat

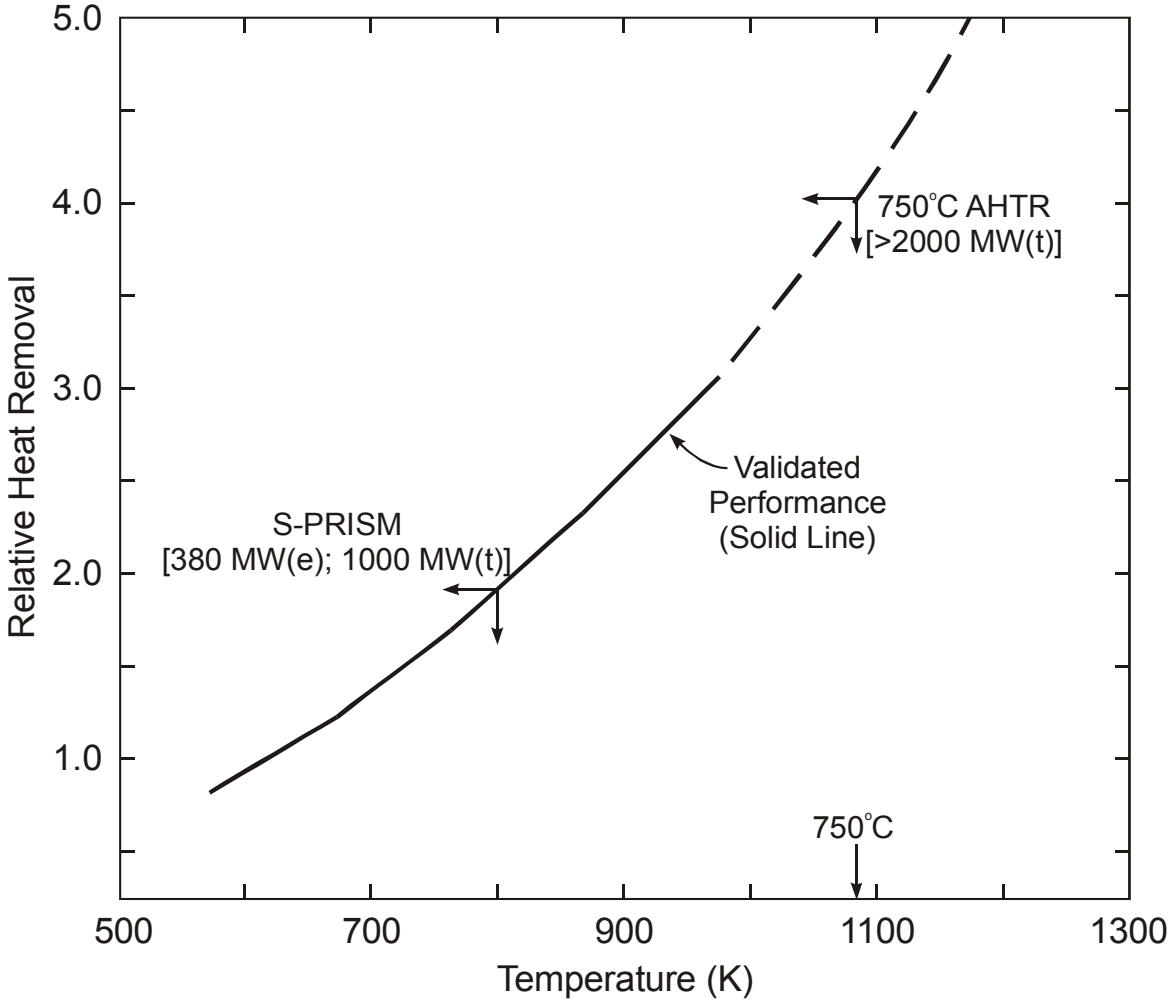
Temperature Gradient Provides Driving Force for Residual Heat Removal



GENERAL ATOMICS

Higher Temperatures of the AHTR Allow Much Larger Reactors with the Same Size Systems

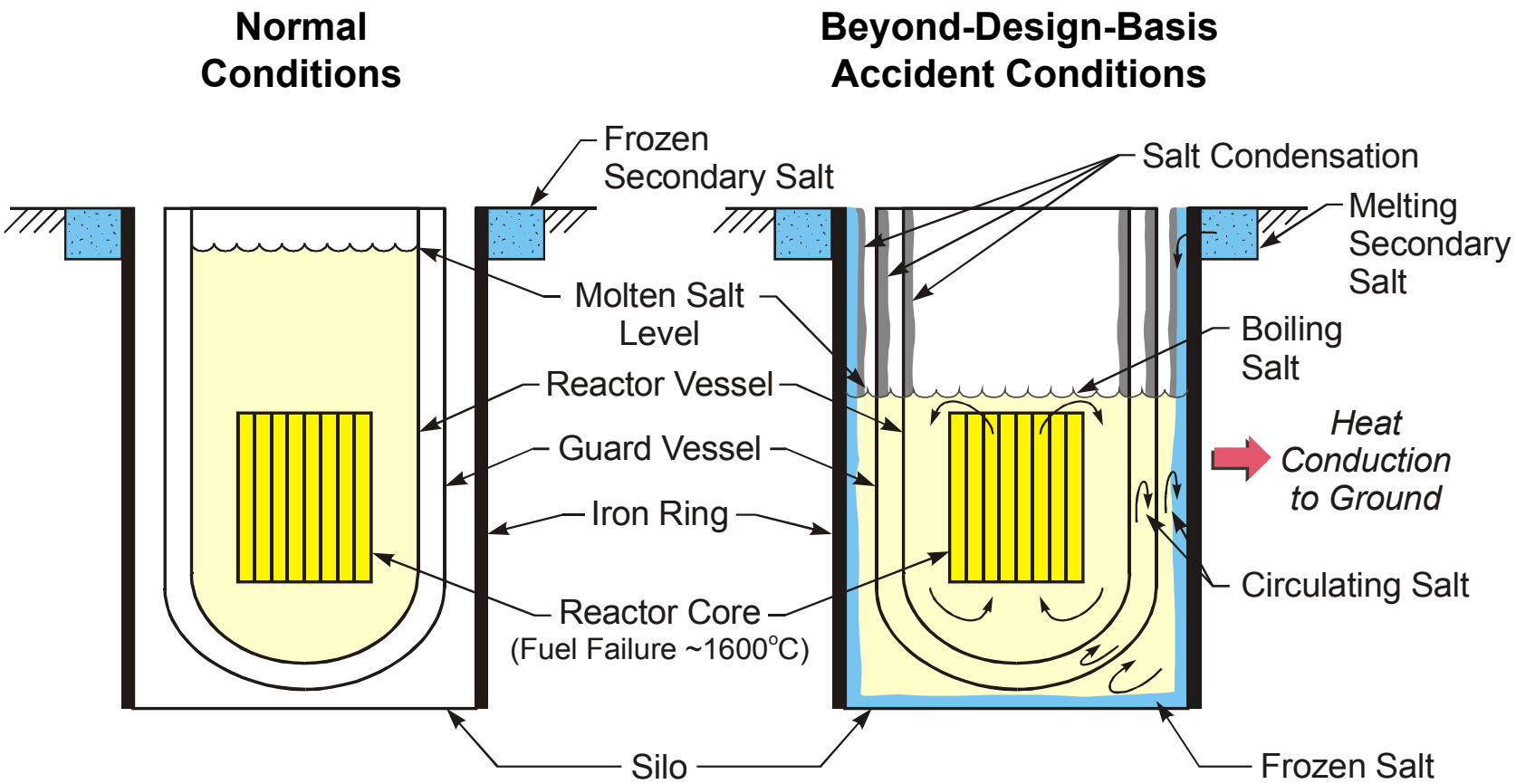
(S-PRISM and AHTR with Identical 9-m Vessels)



Safety Strategy for Beyond Design-Basis Accidents

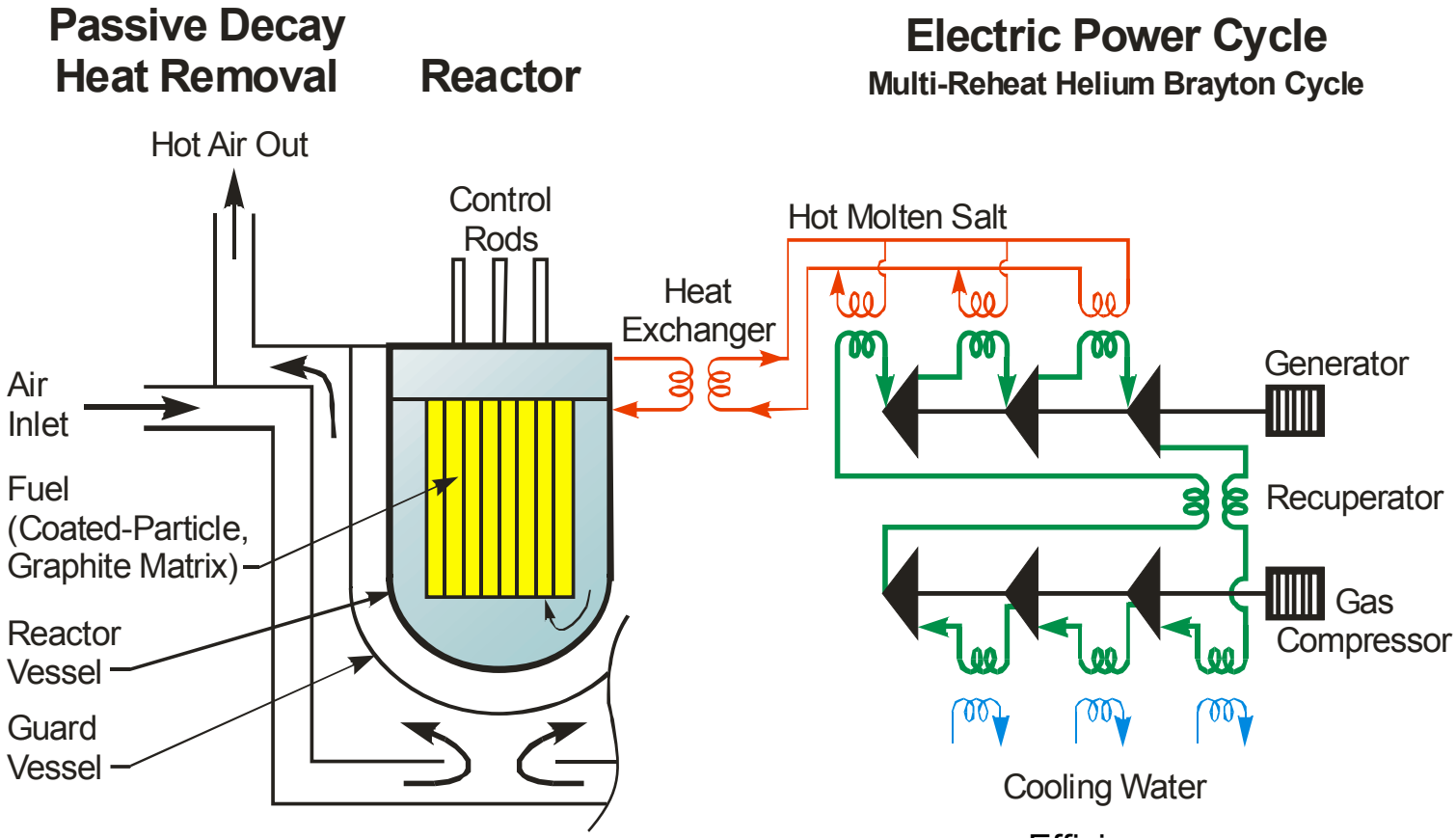
Goal: Walk-Away Safety in a Large Reactor (Same as the Modular Gas-Cooled Reactor)

Beyond-Design-Basis Accident Avoids Radionuclide Release By Decay Heat Conduction To Ground



Liquid-Cooled AHTR Uses a Multi-Reheat Brayton Cycle for High-Efficiency Electricity Production

(AHTR Efficiency at 750°C Equals Gas-Cooled Reactor at 850°C)

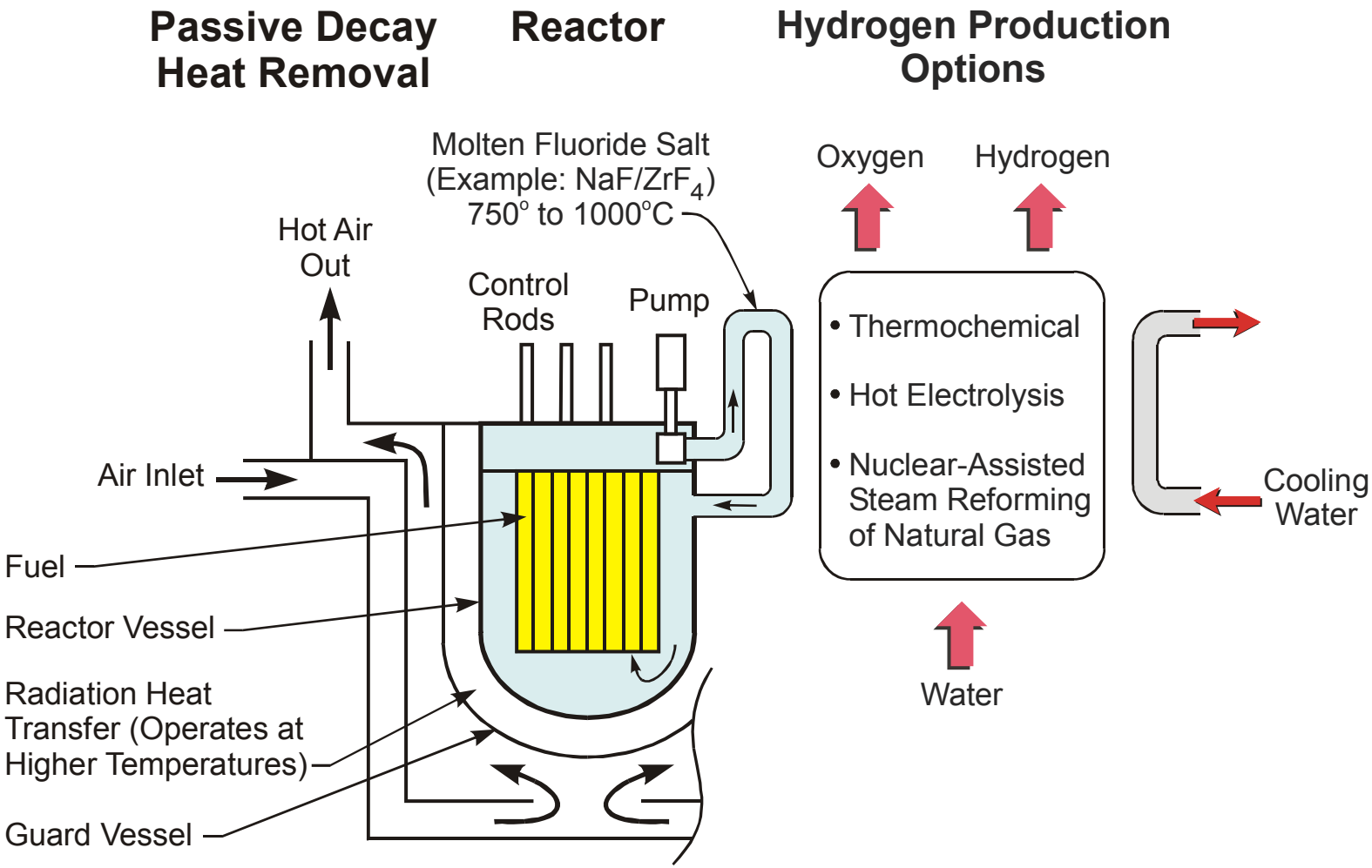


Efficiency
- 48% at 750° C
- 56% at 850° C
- 59% at 1000° C

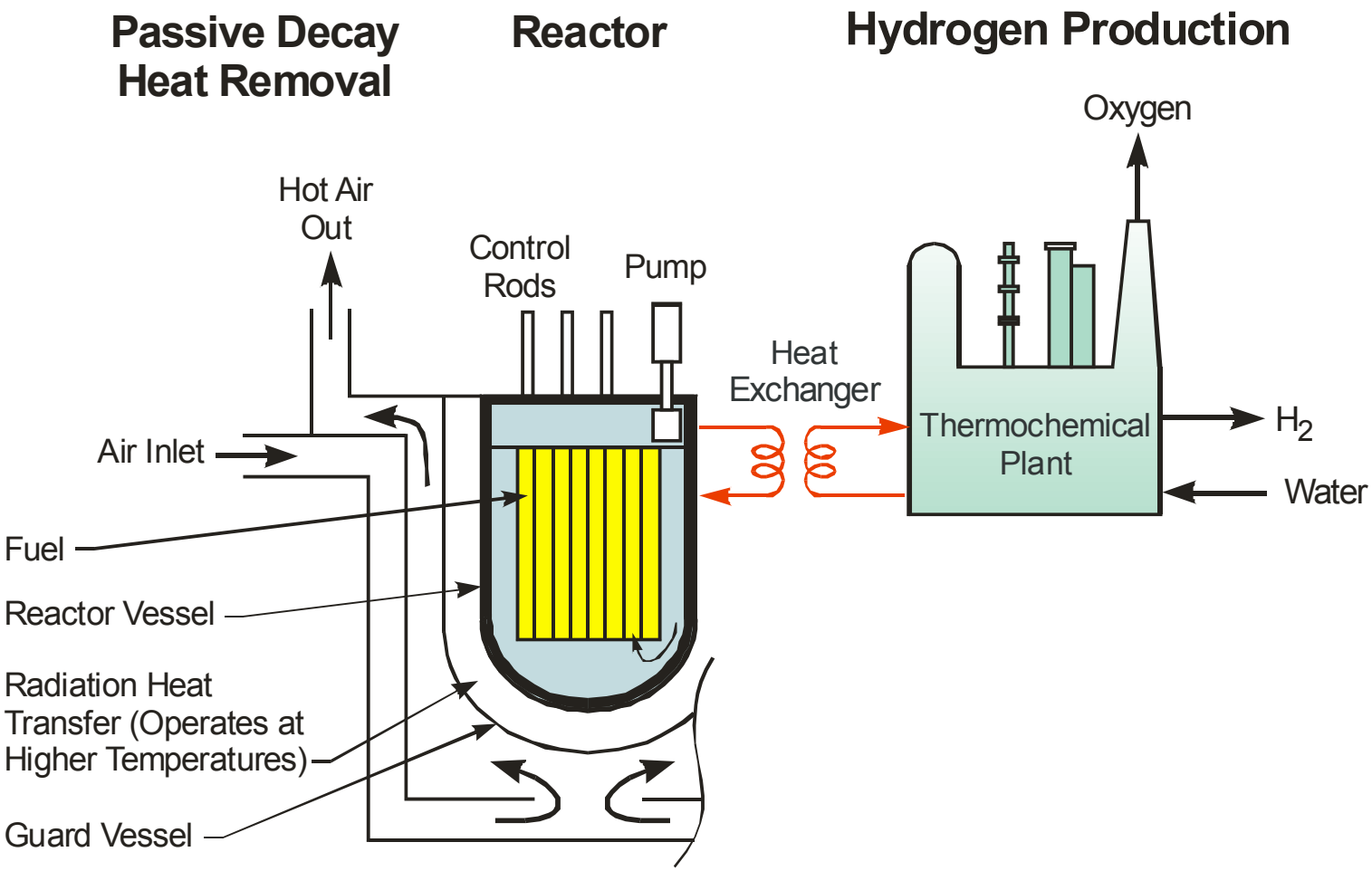
Simple Scaling Laws Estimate AHTR Per Kilowatt Capital Costs at 60% of MHTGR

- Assumptions
  - Size: 2000 MW(t) AHTR and 600 MW(t) MHTGR
  - Traditional scaling factor: 0.7
- Two Factors
  - Size difference
  - Same coolant exit temperature but more heat delivered at higher temperature with AHTR
    - AHTR: 56%
    - MHTGR: 48%

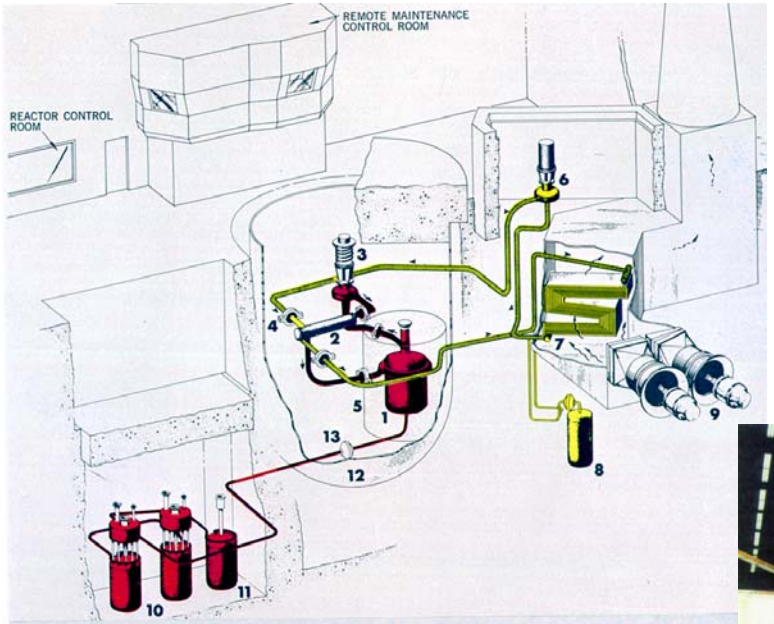
Advanced High-Temperature Reactor



Advanced High-Temperature Reactor



Molten Salt Reactor Experiment (MSRE) Was A Successful Demonstration



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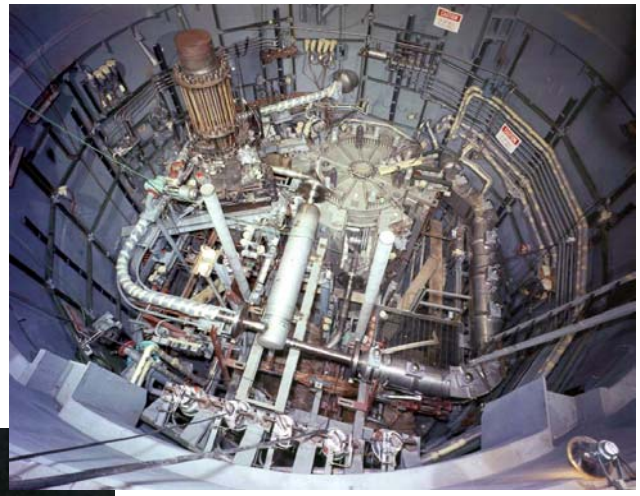
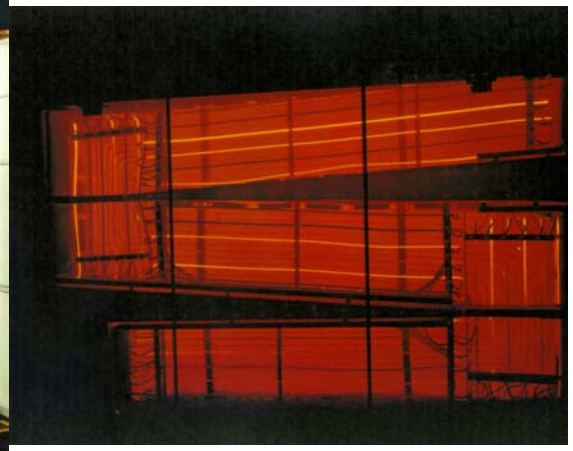
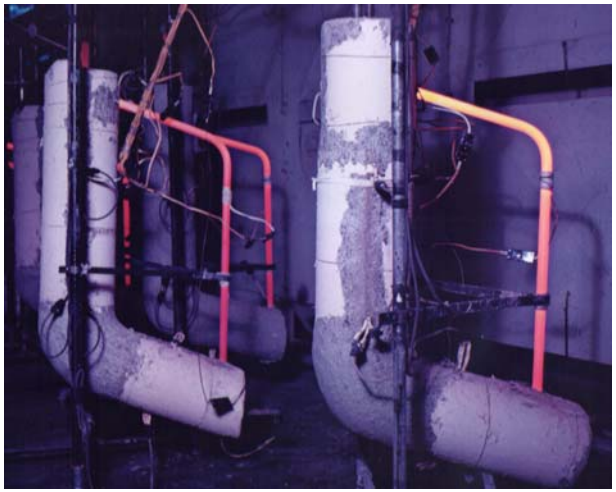




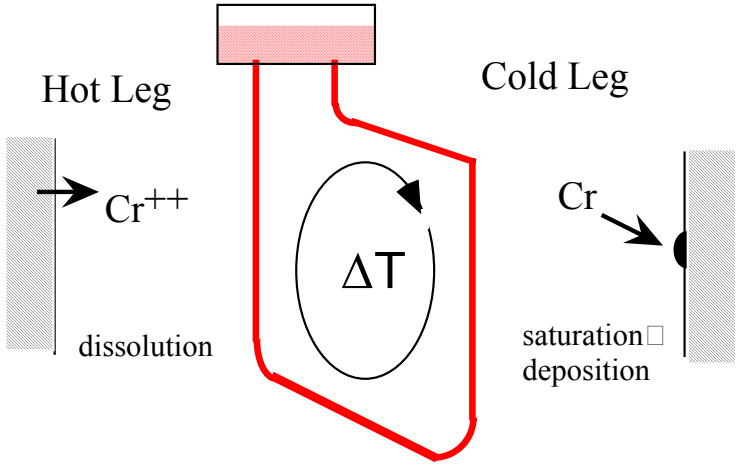
ORNL LDRD is Re-establishing Molten-Salt Testing Capabilities for Gen IV Applications



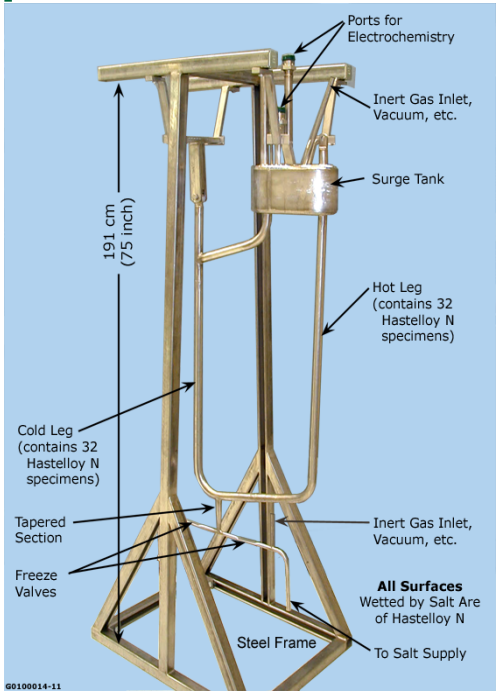
Traditional loops used at ORNL

$$\text{Oxidant} + Cr = \text{Reductant} + CrF_2(d)$$

$$2UF_4(d) + Cr = 2UF_3(d) + CrF_2(d)$$



Key is dynamic loop test



New Corrosion Test Loop w/ on-line electrochemistry, off-gas analysis

New Applications are not driven by breeding:

- **low toxicity (no Be)**
- **low tritium generation (no Li)**
- **very high temperature capability (low vapor pressure, CORROSION CONTROL)**
- **good Minor Actinide Burning characteristics (high trivalent solubility)**
- **acceptable neutronics**